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Model-based Registration of Deaeration Deformation for *in vivo* Animal Lungs

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Purpose

Recent advances in imaging techniques have enabled visualization of minute lung nodules in early-stage cancer, and thoracoscopic surgery is often performed as treatment. Although lung nodules are examined using preoperative CT images, the positions of the nodules change during surgery because of deaeration. Although many models have been reported on modeling hepatectomy [1] and pulmonary respiratory deformation, computation models for deaeration deformation have not been developed.

A past study reported results for the large surface deformation of deflated lungs [2]. This study focuses on the analysis of whole displacement including internal structures.

However, CT intensity shifts during deaeration deformation because the amount of air in a lung in deflated and inflated states differs substantially. Although many studies on image-based registration exist, because image-based registration tends to increase registration error, the CT intensity shift should be addressed to ensure deformation analysis is precise. To address large surface deformation and intensity shift, we propose a model-based algorithm focusing on the surface and centerline data of the bronchus, an internal structure. Intensity shift causes the bronchus regions extracted in the inflated and deflated states to differ so that it is difficult to correspond the local points between the states using bronchus-only based registration. To overcome this difficulty, we propose an algorithm that can register both the lung surface and the entire internal structure of deaeration deformation.

Method

In our framework, a tetrahedral mesh of both the surface and centerline model are used to represent the whole lung structure. Triangulated surfaces of the upper and lower lobes are first reconstructed from their volumetric labels. In this method, the inflated shape is registered to the deflated shape. The registration algorithm consists of the following four steps.

STEP 1

Tetrahedral meshes are generated using the nodes of the inflated surface data and inner point, which is composed of the end-points and bifurcations of these data. For each tetrahedron region, the barycentric coordinates of the existing centerline data in the region are registered.

STEP 2

Surface data are registered using the method in [2] and the tetrahedron region is deformed. The inflated centerline data is moved to avoid changing the barycentric coordinates registered in STEP 1.

STEP 3

The tetrahedron region is deformed by moving the inner points to minimize an evaluation function.

The centerline data are moved as in STEP 2.

STEP 4

Return to STEP 3 until the evaluation value converges.

A larger region is extracted from inflated state data than deflated state data because the number of bifurcations is greater in an inflated state. Hence, the evaluation function measures the distance from each node of the deflated centerline data to that of the inflated data. Additionally, from visual observations of the deaeration deformation, we assume that the shape of the bronchus does not locally deform much during deaeration deformation. Hence, to achieve a spatially smooth deformation, additional constraints are placed on the angle of the centerline data and the rate of increase in the tetrahedral region. The evaluation function is defined as follows.

Here, n/m is the number of vertices of the deflated/inflated centerline data, d_i is the shortest distance from each vertex of the deflated

$$\frac{1}{n}\sum_{i}^{n} d_i + \frac{w}{m}\sum_{i}^{m} |\boldsymbol{n}_j \cdot \boldsymbol{n}_{0j}| + \frac{v}{l}\sum_{k}^{l} |R_k - R_{kmean}| \qquad (1)$$

centerline data to a vertex of the inflated centerline data, $\boldsymbol{n}_i$ is a vector from each vertex of inflated centerline data to an adjacent vertex, and $\boldsymbol{n}_{0i}$ is $\boldsymbol{n}_i$ modified by STEP 3, l is the number of tetrahedron regions, R_k is the rate of increase in volume of the k th tetrahedron region from STEP 3, R_{kmean} is the average rate of increase in volume of the regions adjacent to the k th tetrahedral region from STEP 3, and w and v are weighting parameters.

Result

Experiments were conducted to confirm the accuracy of registration using the proposed algorithm. Three-dimensional (3D) labeled data of the upper/lower lobes and bronchi region of left lung of five *in vivo* Beagle dogs were extracted from a 3D CT image using Synapse VINCENT manufactured by Fuji Film Co. Ltd. to obtain surface data. There are 250 vertices for all surfaces and 500 tetrahedral elements. Bronchi centerline data were converted from label data using the Vascular Modeling Toolkit. These processes are automatically done in the software. We used five data sets, referred to as case *i*, ($i = \{1,2,3,4,5\}$). The inflated centerline data has 1440 – 1692 vertices, the deflated centerline data has 1040 – 1094 vertices, there are 120 – 160 (inflated) and 67 − 124 (deflated) end-points and bifurcations in the data. We used 0.01 for both w and v in (1) after examination of several values.

Figure 1 shows the inflated and deflated shapes of cases 2 and 5 obtained using our algorithm. Here, both the point-to-point correspondence among centerline data and spatially smooth deformation were achieved, even though extracted regions differed between the two states. To evaluate registration error, we selected less than six reference points for each case that correspond visually with the centerline data and compared the coordination obtained from registration and manual pointing. The average TRE of the five cases before surface registration was 6.0 mm, after STEP 2 was 5.0 mm, and after centerline data registration was 2.1 mm.

Conclusion

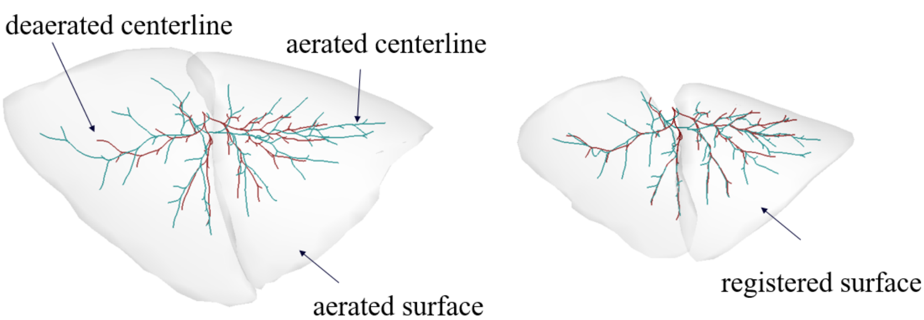
We proposed an algorithm that registers both surface and centerline data for deaeration deformation. This algorithm overcomes the difficulties caused by large surface deformation and intensity shift. The experiment demonstrated that its average registration error is 2.1 mm, which is a clinically viable level. Our future work includes analyzing the displacement of the bronchus and modeling deaeration deformation statistically.

Reference

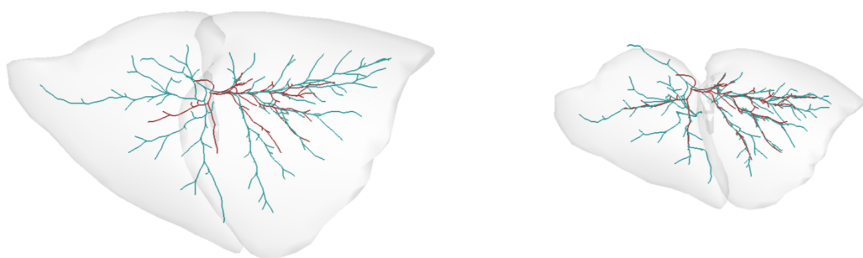
[1] Nakao. M, and Minato. K, (2010), "Physics-based Interactive Volume Manipulation for Sharing Surgical Process, "IEEE Trans. on Information Technology in Biomedicine, Vol.14, No. 3, pp. 809-816.

[2] Kobayashi. K, Nakao. M, Tokuno. J, Chen. T. F, Matsuda. T, (2018), "Analysis of Deaeration Deformation in Ex Vivo Animal Lung by Laplacian-Based Surface Registration", 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society.

Fig. 1 Registration results before surface registration (left) and after centerline data registration (right): (a) case 2, (b) case 5



(a)



(b)